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CONVERTER DESIGN TECHNIQUES AND APPLICATIONS

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ABSTRACT

Transistorized direct current voltage converters offer a number of advantages over other types because of their small size, low weight, high efficiency, high reliability, precision accuracy and wide range of control.

There are three basic types of converter subsystems: series converter in which a voltage-controlled component is placed in series with the load; shunt converter in which a current-controlled component is placed in shunt with the load; and a switching converter in which a voltage-controlled component is turned on and off in series with the load. Converters employing any of these three types of subsystems can provide constant voltage, constant current, or constant impedance across the load.

This paper discusses transistorized voltage converters of the series, shunt, and switching types. Included are design and application considerations, step-by-step design procedures, and the solution to sample design problems.

INTRODUCTION

The function of power converters in aerospace systems is to transfer and transform electric power from the output terminals of a power source (i. e., generator) to other forms as required by specific loads. Efficiency, size, weight, reliability, ripple, regulation, electromagnetic compatibility and stability are important parameters in aerospace power processing systems. The design and application considerations are discussed herein for transistorized voltage converters of the series, shunt, and switching configurations. Power processing systems are made up of power converter subsystems (ref. 1).

A typical series voltage converter is shown in figure 1. In this converter, output voltage (V_O) is sensed by a resistor network (R2 and R3). The analog voltage (V_3) is compared to a reference voltage (V_R) to generate an error signal (V_E) to drive the series component. Bias for the series component is obtained from the generator (V_G) thru resistor (R1). The load resistor (R_O) varies over the range from ($R_O - \Delta R_O$) to ($R_O + \Delta R_O$). The voltage source (V_S) varies over the range from ($V_S - \Delta V_S$) to ($V_S + \Delta V_S$) with a generator resistance (R_G). The voltage appearing at the generator terminals is (V_G).

A typical shunt voltage converter is shown in figure 2. The shunt regulator includes a shunt component and a reference-voltage component. The output-voltage (V_O) remains constant because the shunt-element current (I_{sh}) changes as the load current (I_O) or input voltage (V_S) changes. The shunt element current (I_{sh}) change is reflected in a change of voltage across the resistor (R1) in series with the load.

A typical switching voltage converter is shown in figure 3. The series component serves as a switch and is either shut off or full on (saturated). When the current thru the series component is high, the voltage drop across it is low, so the power dissipated in the series component is minimized. The output voltage is sampled and compared to a reference. The error signal is amplified in the voltage comparator.

The amplified error signal drives the interface component to turn the series component on or off depending on the source or load activity. When the series component is on, the free wheeling diode (D_F) is back-biased by the generator voltage (V_G). During saturation of the series component the voltage across the filter choke (V_F) is the difference between the generator voltage (V_G) and the output voltage (V_O) which is nearly a constant. Since the voltage across the choke during this time is nearly constant, the current through the choke increases linearly with time. When the output voltage reaches a predetermined level, the voltage comparator turns the series component off. When the series component is off, the current in the choke starts to decrease, so the voltage across the choke reverses polarity. This polarity change is in the direction to turn on the filter diode (D_F), and the choke then becomes clamped to the filter capacitor (C_F), which has the output voltage (V_O) across it. The choke current then decreases linearly during the off time interval. When the choke current falls below the load current, the capacitor supplies the difference to the load. This causes the capacitor voltage to fall. When the output voltage falls below a level determined by the voltage reference, the series component is turned back on. The on/off ratio increases with load and decreasing generator voltage.

SERIES CONVERTER DESIGN TECHNIQUE

The step-by-step technique which follows is recommended for the design of transistorized series voltage converters. The design equations used in this technique are derived in Ref. 2. Referring to the block diagram in figure 1

1. Conditions and requirements typical for a spacecraft application:

$$\begin{array}{ll} V_O = 28 \text{ Vdc} & \Delta V_O = \pm 0.1 \text{ Vdc} \\ V_S = 56 \text{ Vdc} & \Delta V_S = \pm 6 \text{ Vdc; solar array battery buffered.} \end{array}$$

$$R_G = 7 \text{ ohms}$$

$$R_O = 40 \text{ ohms} \quad \Delta R_O = \pm 15 \text{ ohms}$$

Spacecraft baseplate temperature -55° to $+60^\circ$ C

2. Select a silicon reference diode

Usually $0.2 V_O \leq V_R \leq 0.9 V_O$; choose

$$V_R \approx 0.5 V_O \approx 14 \text{ Vdc use } 15 \text{ Vdc}$$

The values of V_R , ΔV_O and circuit gain are all interrelated. Higher values of V_R minimize circuit gain for a given ΔV_O .

In selecting electronic components, a reasonable value of temperature rise (ΔT) for the components must be determined. Typical values are 15° C for ΔT .

Motorola type (Ref. 3)	IN965B	IN4109
Power rating at 75° C	368	140 mW
Current rating at 75° C	24.5	9.35 mA
Cost	2.95	3.85 \$

Reference supply (I_{RS}) = 10 mA typical

$$\text{Power dissipation (PD}_{RC}) = V_R \times I_{RS} = 150 \text{ mW.}$$

Select IN965B for reference diode

3. Determine V_3

V_3 is a function of V_R , typically $V_3 = V_R$

$$\therefore V_3 = 15.0 \text{ Vdc}$$

4. Select a series component

$$I_O = 0.70 \text{ Adc} \quad \Delta I_O = +0.42$$

$$-0.19$$

$$V_{CE_{\max}}(\text{steady state}) \geq V_s + \Delta V_s - V_o \left(1 + \frac{R_G}{R_o + \Delta R_o}\right) - \Delta V_o \geq 56$$

$$+ 6 - 28 \left(1 + \frac{7.0}{55}\right) - 0.1 \geq 30.3 \text{ Vdc}$$

$$V_{CE_{\min}} \leq V_s - \Delta V_s - V_o \left(1 + \frac{R_G}{R_o - \Delta R_o}\right) + \Delta V_o \leq 56$$

$$- 6 - 28 \left(1 + \frac{7}{25}\right) + 0.1 \leq 14.2 \text{ Vdc}$$

$$I_{C_{\max}} = I_{O_{\max}}$$

$$PD_{T_{\max}} = (V_s + \Delta V_s - V_o - \Delta V_o) I_{C_{\max}} - \left(I_{C_{\max}}\right)^2 (R_G)$$

$$\approx 34(1.12) - (1.12)^2(7) = 29.2 \text{ Wdc at a maximum case}$$

temperature of 75° C. Consider

Motorola type (NPN)	2N4231	2N4233
$BV_{CEO_{\max}}$	40	80 Vdc
$V_{CE_{\text{sat}}_{\max}}$	2.0	2.0 Vdc
$I_{C_{\max}}$	1.5	1.5 Adc
$PD_{T_{\max}}$ at 75° C	28.0	28.0 W
h_{FE} at 0.70 Adc	50	50
V_{EB}	5.0	5.0 Vdc

h_{fe}	30	30
g_m at 75°C	4.0	4.0 mhos
Cost	2.10	3.20 \$

Choose the 2N4231

5. Select a Darlington driver

Choose $I_{Bn} = 1.0 \text{ mAdc}$ = input base current of n^{th} transistor

$$h_{FE_1} h_{FE_2} \dots h_{FE_n} = \frac{I_{C1}}{I_{Bn}} = \frac{0.70}{1 \times 10^{-3}} = 700$$

$$h_{FE_2} \geq \frac{I_{C1}}{I_{Bn}} \cdot \frac{1}{h_{FE_1}} = \frac{700}{50} = 14$$

$$I_{C2} = I_{B1} = \frac{I_{C1}}{h_{FE_1}} = \frac{0.70}{50} = 15 \text{ mAdc}$$

$$\begin{aligned} PD_{T(\text{max})} &\approx (V_{CE_1} - V_{BE_1}) I_{C2} = (30.3 - 0.7) 15 \times 10^{-3} \\ &= 29.6 \times 15 \times 10^{-3} = 445 \text{ mW} \end{aligned}$$

Consider Motorola type (NPN)	2N3946	2N3947
$BV_{CEO_{\text{max}}}$	40	40 Vdc
$I_{C_{\text{max}}}$	200	200 mAdc
$PD_{T_{\text{max}}}$ at 75°C	0.96	0.96 W
h_{FE} at 15 mAdc	100	150
V_{EB}	6.0	6.0 Vdc

g_m	0.25	0.35 mho
Cost	2.40	2.65 \$

Choose 2N3946

6. Solve for $V_{BE_{21}}$, where

$$V_{BE_{21}} = V_{BE_2} + V_{BE_1} = 0.77 + 0.83 = 1.60 \text{ Vdc}$$

7. The design-center value for V_{CE_1} is given by

$$V_{CE_1} = V_s - V_o - \frac{V_o R_G R_o}{R_o^2 - \Delta R_o^2} = 56 - 28 - \frac{(28)(7)(40)}{(40)^2 - (15)^2} = 22.3 \text{ Vdc}$$

8. Solve for R_1

$$R_1 = \frac{V_{CE_1} - V_{BE_{21}}}{I_{B2}} = \frac{22.3 - 1.60}{1 \times 10^{-3}} = 20.8 \text{ K ohms}$$

Use 21 K ohms

9. Solve for $g_{m3} = \frac{\Delta I_C}{\Delta V_{BE}}$; where g_{m3} is the mutual conductance of the amplifier component (transistor).

$$\Delta V_o = \frac{\Delta V_s + \frac{V_o}{R_o^2} \left(R_G + \frac{1}{g_{m1}} \right) \Delta R_o}{1 + g_{m3} R_1 \frac{V_3}{V_o} + \frac{R_G}{R_o} + \frac{1}{R_o g_{m1}}}$$

$$g_{m3} = \frac{1}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}h_{fe1}}} = \frac{1}{\frac{1}{4} + \frac{1}{(0.25)30}} = 2.61 \text{ mho, where}$$

$$0.1 = \frac{6 + \frac{28}{1600} (7 + 0.38)15}{1 + g_{m3} \frac{(1500)(15)}{28} + \frac{7}{40} + \frac{1}{(40)(4)}}$$

$$0.1 = \frac{7.94}{1.181 + 804 g_{m3}} \quad g_{m3}^c(\text{min}) = \frac{7.82}{80.4} = 0.097 \text{ mho}$$

where g_{m3}^c is the calculated value (minimum value desired) of mutual conductance.

10. A third Motorola 2N3946 can be used as the amplifier component; at this current level ($\sim 14 \text{ mAdc}$):

$$g_{m3}^D \cong 0.15 \quad h_{FE_{\min}} \cong 40$$

where g_{m3}^D is the mutual conductance of the selected transistor and obtained using Ref. 3.

Since $g_{m3}^D > g_{m3}^C$ only one amplifier stage is needed for this case

11. Select R_2 and R_3 as follows:

Choose $I_3 = 10 \text{ mAdc}$ (typically $I_3 < 1\% I_0$ to minimize power dissipation).

$$V_3 \simeq V_R = 15.0 \text{ Vdc}$$

$$R_3 = \frac{V_3}{I_3} = \frac{15}{10 \times 10^{-3}} = 1500 \text{ ohms neglect } I_R$$

$$R_2 = \frac{V_o - V_3}{I_3} = \frac{28 - 15}{10 \times 10^{-3}} = 1300 \text{ ohms}$$

Use 1300 ohms (the nearest standard value, 1200 ohms would result in a 4% error in V_o).

The complete regulator circuit is shown in figure 4.

12. Efficiency considerations;

$$\eta_{\text{rated}} = \frac{P_o}{P_o + P_L} \times 10^2 = \frac{19.6}{38.9} \times 10^2 \cong 50.3\% \text{ where}$$

$$P_o = (0.70)(28) = 19.6 \text{ W}$$

$$P_L = (0.70)(4.9 + 22.3) + (0.011)(28) = 19 + 0.3 = 19.3 \text{ W}$$

SHUNT CONVERTER DESIGN TECHNIQUE

A step-by-step technique for the design of shunt converters is explained in this section. Equations used in this example are derived in Ref. 2. Referring to the block diagram in figure 2.

1. Conditions and requirements similar to those used for the series example:

$$V_o = +28 \text{ Vdc} \quad \Delta V_o = \pm 0.0125 \text{ Vdc}$$

$$V_s = +56 \text{ Vdc} \quad \Delta V_s = \pm 6 \text{ Vdc}$$

$$R_o = 40 \text{ ohms} \quad \Delta R_o = \pm 15 \text{ ohms}$$

$$R_G = 7 \text{ ohms}$$

$$\text{Spacecraft baseplate temperature } -55^{\circ} \text{ to } +60^{\circ} \text{ C}$$

2. Select a shunt component:

$$I_{sh_{max}} = I_{O_{max}} = 1.12 \text{ Adc where } I_{O_{max}} = \frac{V_O + \Delta V_O}{R_O - \Delta R_O}$$

$$= \frac{28.0125}{40 - 15} = 1.12 \text{ A}$$

$I_{sh_{max}}$ is defined as the limiting case which exceeds the maximum value of I_{CE} obtained with a load equal to $R_O - \Delta R_O$

$$V_{sh_{max}} \leq V_O + \Delta V_O \approx 28 \text{ Vdc (forward biased steady state)}$$

$$PD_{sh_{max}} = I_{sh_{max}} V_{sh_{max}} = (28)(1.12) = 31.4 \text{ W at } 75^\circ \text{ C. Consider}$$

Motorola type (Ref. 3)	MJE205	2N4921
BV_{CEO}	50	40 Vdc
$I_{C_{max}}$	5.0	3.0 Adc
h_{FE} at 1.0, 0.5 Adc	50	45
$V_{CE_{sat}}$ at 1.5, 0.5 Adc	0.5	1.0 Vdc
PD at 75° C	38	21.6 W
Cost	2.10	1.33 \$

Choose the MJE205

3. Select the base-to-emitter resistor for the shunt component:

Let $I_2 = 1.5 \text{ mAdc}$, typically $I_2 \leq 1\% I_O = 11.2 \text{ ma}$

$$V_{BE_1} = 0.8 \quad V_{BE_2} = 0.7 \text{ Vdc (on bias two stages)}$$

$$R_2 = \frac{V_2}{I_2} = \frac{1.5}{1.5 \times 10^{-3}} = 1000 \text{ ohms}$$

neglecting $I_3 \ll I_2$

4. Select the number of stages required in the shunt component:

$$\text{Total } B = \frac{1.12 \text{ A}}{0.001} = 1120$$

$$\text{Number of stages } (h_{FE} \cong 50 \text{ for each stage}) = 50^n \geq 1120$$

$$n = 2$$

Choose a two stage series component.

5. For the second stage Q2:

$$h_{FE2} = \frac{h_{FE}}{h_{FE1}} = \frac{1562}{39.1} = 39.1$$

$$I_{C2} = \frac{I_1}{h_{FE1}} = \frac{0.70}{50} = 14 \text{ mAdc}$$

Motorola type (Ref. 3)	2N3946	2N3947
$BV_{CEO_{max}}$	40	40 Vdc
$I_{O_{max}}$	200	200 mAdc
$PD_{T_{max}}$ at 75° C	0.96	0.96 W
h_{FE} at 14 mAdc	100	150
Cost	2.40	2.75 \$

Choose the 2N3946

6. Select a reference component (RC)

Let $R_f \leq 5$ ohms

$$V_R = V_o - V_2 = 28 - 1.5 = 26.5 \text{ Vdc}$$

$$I_{1_{max}} = I_2 + I_3 = 1.5 + 0.14 = 1.64 \text{ mAdc}$$

$$PD_{RC} = 26.5(1.64) = 43.5 \text{ mW at } 75^\circ \text{ C. Consider}$$

Motorola type (Ref. 3)	IN4750	IN971
Selected zener voltage	26.5 ±1.0%	26.5±1.0% Vdc
PD _Z at 75 ^o C	0.93	0.35 W
I _R _{max}	34	15 mAdc
Z _{zt} _{max} at 9.5 mAdc	35	41 ohms
Cost	1.26	2.35 \$

Choose the IN4750 (selected)

7. Select a series resistor component:

$$V_S - \Delta V_S = V_O + (R_G + R_1)I_G$$

$$56 - 6 = 28 + (R_G + R_1)0.70$$

$$22 = (R_G + R_1)0.70$$

$$R_1 = 31.5 - 7 = 24.5 \text{ ohms}$$

Choose 24 ohms (closest standard value).

The complete circuit for the transistorized shunt voltage converter is shown in figure 5.

8. Efficiency considerations:

$$\eta = \frac{P_O}{P_O + P_L} \times 10^2 = \frac{19.6}{19.6 + 29.5} \times 10^2 = 38.9$$

$$P_O = V_O I_O = (28)(0.70) = 19.6 \text{ W}$$

$$P_L = I_G(R_G + R_1) + (I_{sh} + I_{C2} + I_1)V_O$$

$$= (0.70)(31.5) + (0.266)(28) = 29.5 \text{ W}$$

SWITCHING CONVERTER DESIGN TECHNIQUE

A step-by-step technique for the design of switching converters is explained in this section. Equations used in this example are derived in Refs. 4 and 5. The block diagram of a switching converter is illustrated in figure 3.

1. Conditions and requirements similar to those used for the series example:

$$V_o = +28 \text{ Vdc} \quad \Delta V_o = \pm 0.030 \text{ Vdc}$$

$$V_s = +56 \text{ Vdc} \quad \Delta V_s = \pm 6 \text{ Vdc}$$

$$R_o = 40 \text{ ohms} \quad \Delta R_o = \pm 15 \text{ ohms}$$

$$R_G = 7 \text{ ohms}$$

Spacecraft baseplate temperature -55° to $+60^\circ$ C

2. Select a choke for the output filter using energy considerations with Kirchoff's laws:

$$L_F = \frac{(V_s - V_o)V_o}{2fV_s(\Delta I_o)} = \frac{(56 - 28)(28)}{(2)(2.5 \times 10^4)(56)(0.25)} = 1.12 \text{ mH, where } f \text{ is}$$

the desired frequency at maximum load

An air gaped 'C' core would be best suited for the choke component

3. Select a capacitor for the output filter:

$$C_F = \frac{(V_s - V_o)V_o}{8f^2(\Delta V_o - \Delta H)L_F V_s} = \frac{(56 - 28)(28)}{8(2.5 \times 10^4)^2 (6 \times 10^{-2})(1.12 \times 10^{-3})(56)}$$

$C_F = 29.5 \mu\text{F}$ where ΔH is the hysteresis of the voltage comparator which in the case for a differential input amplifier is assumed to be zero.

Use 2, 15 $\mu\text{F} \pm 10\%$, 50 WVDC aluminum electrolytes in parallel to minimize equivalent series resistance

4. Select a transistor for the series switching component:

$$I_{C_{\max}} \geq 1.0 \text{ Adc}$$

Assuming a converter efficiency of 80%, the following relationship for transistor power dissipation is:

$$PD_T - 0.2 P_O = (0.2)(28)(0.75) = 4.2 \text{ W at } 75^\circ \text{ C}$$

$$V_{CEO} \geq 62 \text{ Vdc} \quad V_{CE_{\text{sat}}} \leq 0.3 \text{ Vdc}$$

$$t_{T(\text{on})} = t_{T(\text{off})} \leq 0.3 \mu\text{sec (switching times). Consider}$$

Motorola type (Ref. 3)	2N4912	2N4923
$I_{C_{\max}}$ at $I_B = 0.1 \text{ Adc}$	1.0	1.0 Adc
PD_T at 75° C	20	21 W
V_{CEO}	80	80 Vdc
V_{CES}	0.3	0.3 Vdc
f_T	3.0	3.0 MHz
$t_{T(\text{on/off switching time})}$	0.3	0.3 μsec
Cost	2.10	1.80 \$

Use the 2N4923.

5. Select a diode for the output filter (Ref. 7):

$$I_{D_{\max}} = 1.0 \text{ Adc} \quad PIV_D \geq 28 \text{ Vdc}$$

$$t_{fr} \leq 0.2 \mu\text{sec} \quad t_{rr} \leq 0.3 \mu\text{sec. Consider}$$

Unitrode type (Ref. 6)	UTR 02	UTX 205
$I_{D_{\max}}$ at 75° C	1.54	1.54 Adc
PIV_D	50.0	50.0 V
t_{fr}	0.1	0.01 μsec
t_{rr}	0.25	0.075 μsec
Cost	1.55	3.55 \$

Use UTR 02.

6. Efficiency considerations.

$$\eta = \frac{P_o}{P_o + P_L} \times 10^2 = \frac{19.6}{19.6 + 2.9} \times 10^2 = 87.2\%$$

$$P_o = (28)(0.70) = 19.6$$

Losses:

$$\text{a. Choke dc loss} = I_o^2 R_{CH} = (1.12)^2 (1) = 1.26 \text{ W}$$

$$\text{b. Choke ac loss} = \left(\frac{f^2 L^2}{6Q} \right) \left[\frac{V_s I_{\max}^3 - I_o^3}{V_o (V_s - V_o)} \right]$$

$$= \left[\frac{(2.5 \times 10^4)^2 (1.12 \times 10^{-3})^2}{(6)(20)} \right] \left\{ \frac{56 [(1)^3 - (0.70)^3]}{28(56 - 28)} \right\}$$

$$= 0.216 \text{ W}$$

$$\text{c. Transistor on loss} \cong \frac{V_{CEsat} V_o I_o}{V_s} = \frac{(0.3)(28)(0.70)}{56}$$

$$= 0.104 \text{ W}$$

$$\text{d. Diode on loss} \cong V_{fr} I_o \frac{(V_s - V_o)}{V_s} = \frac{(0.6)(0.70)(28)}{56}$$

$$= 0.21 \text{ W}$$

e. Transistor switching losses:

$$\begin{aligned}
 fI_P V_S t_{rr(off)} + \frac{fV_S I_{max} \left[t_{T(off)}^2 + t_{rr(off)}^2 \right]}{6t_{T(off)}} &= (3)(56)(0.25 \times 10^{-6})(2.5 \times 10^4) \\
 &+ \frac{(2.5 \times 10^4)(56)(1)(0.09 \times 10^{-12} + 0.06 \times 10^{-12})}{(6)(0.3 \times 10^{-6})} \\
 &= 1.05 + 0.0128 = 1.063 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{f. Auxiliary circuit losses} &\cong \frac{V_{B^1_0} I_0 V_o}{h_{FE} V_S} = \frac{(5)(1.12)(28)}{(10)(56)} \\
 &= 0.28 \text{ W}
 \end{aligned}$$

$$\text{Total losses} = \sum_{i=a}^f P_i \cong 3.13 \text{ W}$$

The complete schematic at the switching converter is shown in figure 6. The design techniques for the auxiliary circuit components are explained in existing literature (see Ref. 8). The important requirements for these circuits are that hysteresis be held to a minimum and rise and fall times are less than the series component.

A study of optimum methods to transfer and transform electric power in aerospace applications showed that no single method was best for all cases. The optimum method was very much dependent upon available devices, generating sources, and load parameters. These are constraints difficult to identify for future aerospace missions.

Table I shows some of the important typical converter parameters to consider when faced with the task of choosing the type of converter for use in a given mission.

Low efficiency increases power source area and raises costs; i. e., solar arrays cost about \$8000 per square foot at about 4 watts per square foot. It is not unusual to spend \$10⁶ for a 500 watt, 125 square foot array.

CONCLUDING REMARKS

The design of transistorized voltage converters of the series, shunt, and switching types are developed and explained in this paper.

Past aerospace missions have used either the series, shunt and switching converters or combinations thereof to transfer and transform electric power. The shunt converter has the smallest size, lowest weight and parts count. Regulation and stability are very good but efficiency is poor. The series converter is somewhat larger in size, heavier, uses more parts and has an order of magnitude (10 to 1) decrease in regulation performance than the shunt converter. Stability of both types are good at light or full loads. A ten percent increase in efficiency justifies its use in some cases.

Many current aerospace missions are going to some form of the switching converter. It tends to be a compromise with increased size, weight, and circuit complexity to gain in efficiency and regulation over a series converter. A switching converter will usually exhibit ringing in the output filter for some types of loads so it has only fair stability performance.

The best designed product is only as good as the people and materials finally used to make it. The task of determining that people with the required skills and materials of the proper specified quality are used to build a product must be included in power processor design by other means. This task requires participation of many disciplines including rigorous reliability and quality assurance engineering (Ref. 9).

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TABLE I. - TYPICAL CONVERTER COMPARISON

Type	Efficiency, percent	Size	Weight	Parts count	Regulation	Stability
Series	50	1.1	1.2	7	± 0.10	Good
Shunt	40	1.0	1.0	5	± 0.0125	Good
Switching	85	1.3	1.6	24	± 0.03	Fair

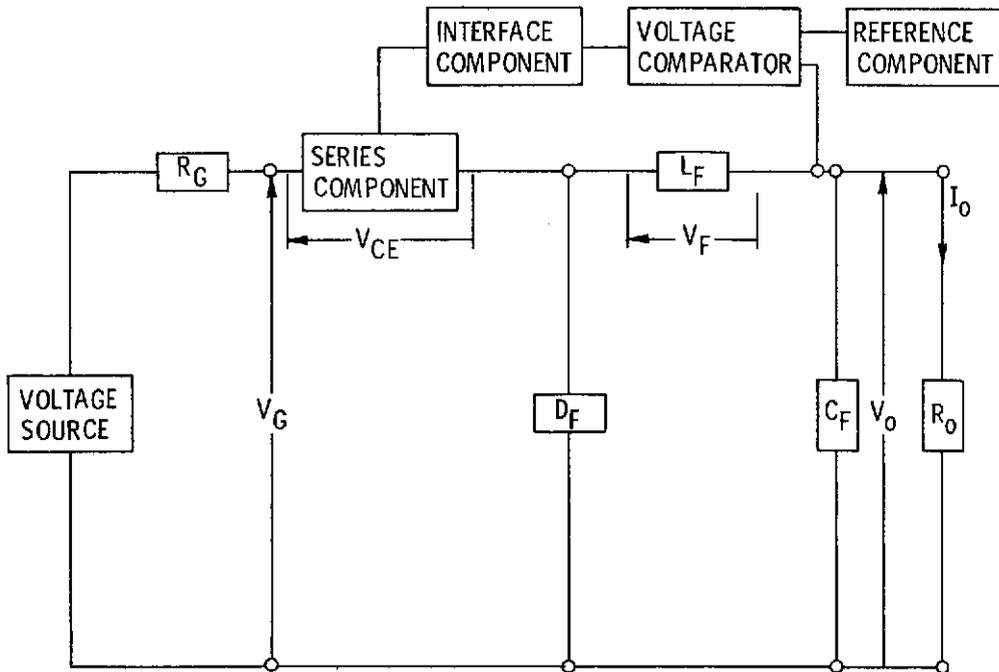


Figure 3. - Typical switching voltage converter.

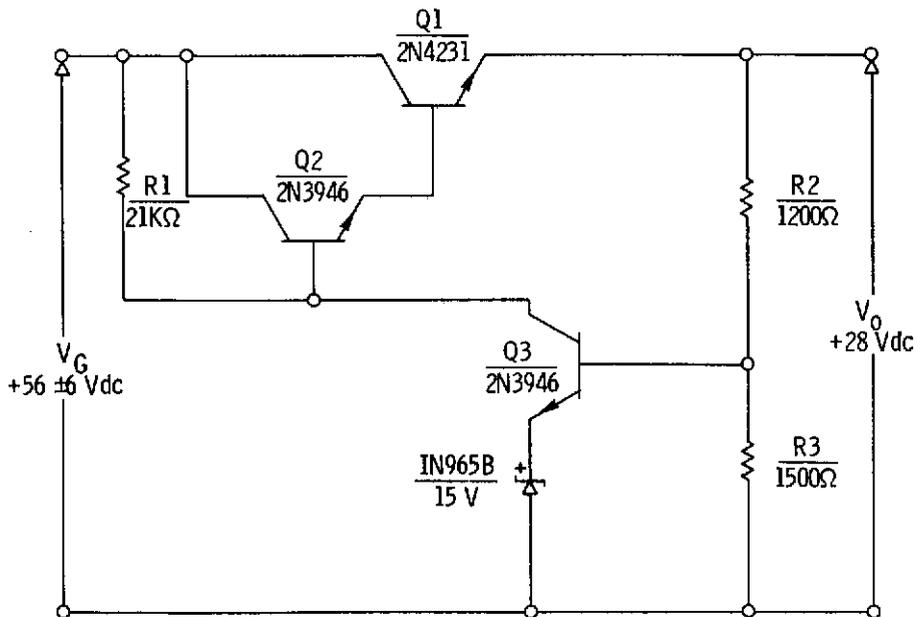


Figure 4. - Schematic diagram for 28 V series converter.

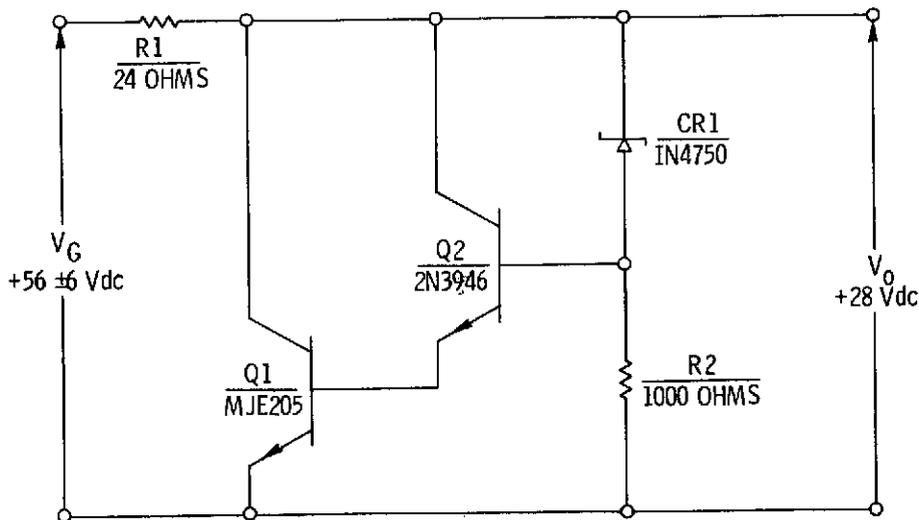


Figure 5. - Schematic diagram for 28 V shunt converter.

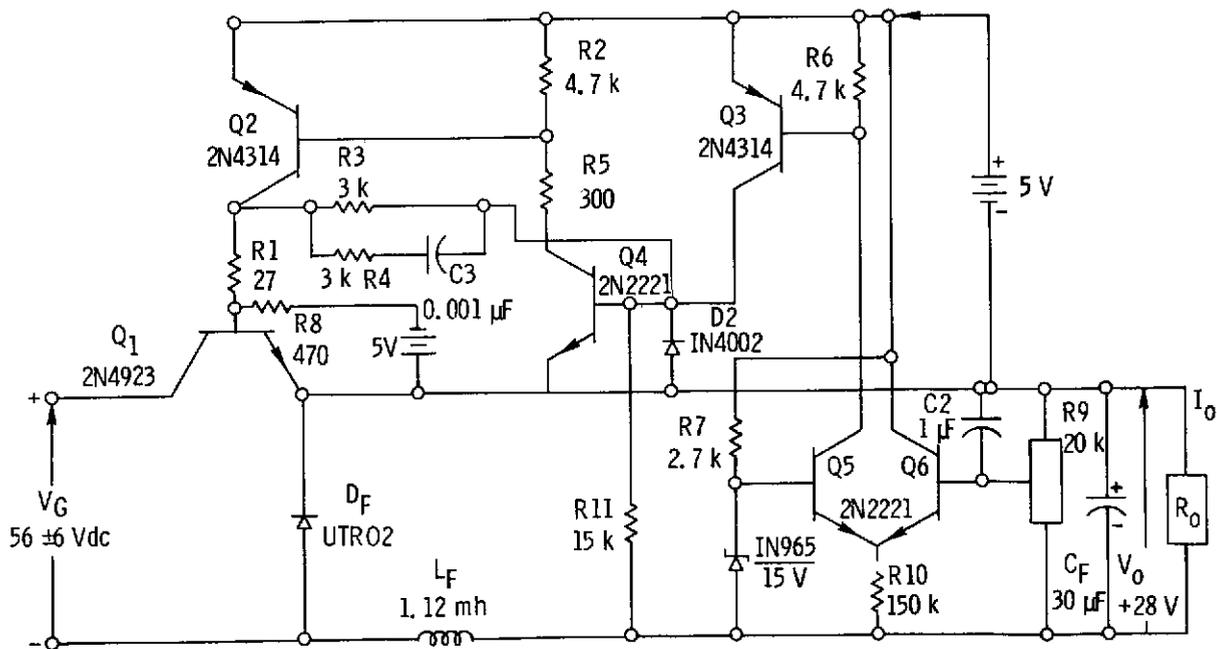


Figure 6. - Schematic diagram for 28 V switching converter.

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